Improvement of traffic flux introduction with a new lane-change protocol with Intelligent Transport Systems

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Abstract

A new Cellular Automata traffic model based on Revised S-NFS model which takes traffic density ahead of a car in next 50m into consideration into a decision making of whether a lane change would be tale or not is established. It is intended to apply as one of the protocols to improve traffic efficiency in premise with Intelligent Transport Systems (ITS) that is able to provide information on traffic density next hundred meters in front of a focal vehicle. A series of systematic simulations reveals that the presented lane changing protocol enhances traffic flux vis-à-vis the conventional lane change rule based on the traditional incentive criterion and safe criterion. Social dilemma analysis suggests our new protocol mitigate strong social dilemma encouraged by a competition between a cooperator; not intending any lane changes and a defector; trying to lane change to minimize his own travel time.

1. Introduction

Traffic jam has been one of the most pressing social problems in urban areas, especially in a megacity in developing countries. A traffic jam not only imposes significant amount of time wasting to an individual, but also brings energy waste as well as air pollution. Therefore, diminishing traffic jam is strongly demanded to dedicate for solving urban environmental problem. Since a road can be regarded as a limited resource, a vehicles running on the road consumes this resource. From the 'public goods' view point, although each vehicle should drive as little as causing traffic turbulence that triggers a stop-and-go wave, a vehicle, in reality, tries to minimize his own travel time even exploiting other vehicles. One of such 'egocentric' behaviors is lane changing, in which a vehicle is motivated to move to a neighboring traffic lane so as to maximize a chance to accelerate than staying current lane (incentive criterion) [1]. As previous studies revealed ([2] – [6]), frequent lane changing causes serious social dilemma classified as multi-player type Prisoner's Dilemma.

Meanwhile Intelligent Transport Systems (ITS), backed by information science and technology, has been expected to mitigate various traffic problems, especially heavy traffic jam in urban areas. If a vehicle would be given meaningful information to help his decision-making, global traffic flux might be kept at a reasonable level without degrading individual payoff that might be evaluated individual travel time.

This study intends to pose a new lane changing protocol instead of the conventional incentive criterion that can be realized by ITS. First off, we establish a Cellular Automata (CA) model to implement such a lane change rule as well as conventional one. Subsequently, we explore whether our new protocol really improves traffic flux by a series of simulations. We also evaluate how the presented lane change protocol mitigate a social dilemma as compared with the conventional rule does.

2. Model description

2.1 Revised-S-NFS model

In this work, we adopt Revise S-NSF model [7], which was confirmed to reproduce Three-phase theory by Kerner [8]. It is because, unlike Nagel-Schreckenberg (NaSch) model [9]; which is the classical and most commonly used CA model, Revised S-NFS model can take account of the influence resulting from an inter-vehicular distance through Random-brake (RB) sub-model. The model also take account various commonly observed actions taken by a driver such as: slow-to-start (S2S), quick start (QS), and random braking (RB). S2S implies an inertial effect, which is important for producing metastable states in fundamental diagrams. QS results from an acceleration or deceleration by a driver who is anticipating the intentions of both the precedent vehicle and several further precedent vehicles.

Revised S-NFS model contains 6 rules as follows;

Rule 1. "Acceleration"

$$v_i^{(1)} = \min\left[V_{\max}, v_i^{(0)} + 1\right]$$

(only if $g_i \geq G \wedge v_i^{(0)} \leq v_{i+1}^{(0)}$ then Rule 1 is applied).

Rule 2. "Slow-to-start (S2S)"

$$v_i^{(2)} = \min\left[v_i^{(1)}, x_{i+s_i}^{t-1} - x_i^{t-1} - s_i\right]$$

(only if rand() $\leq$ q then Rule 2 is applied) and (if rand() $\leq$ r then $s_i = S$ else $s_i = 1$).

Rule 3. "Perspective (Quick start; QS)"

$$v_i^{(3)} = \min\left\lfloor v_i^{(2)}, x_{i+s_i}^t - x_i^t - s_i \right\rfloor$$

Rule 4. "Random brake (RB)"

$$v_i^{(4)} = \max\left\lfloor 1, v_i^{(3)} - 1 \right\rfloor$$

(only if rand() <1−p_i then Rule 4 is applied).

$if\ (g_i \geq G)$

$p_i = P_1$

$if\ (g_i < G)$

$p_i = P_2$ for $v_i^{(0)} < v_{i+1}^{(0)}$

$p_i = P_3$ for $v_i^{(0)} = v_{i+1}^{(0)}$

$p_i = P_4$ for $v_i^{(0)} > v_{i+1}^{(0)}$

Rule 5. "Avoid collision"

$$v_i^{(5)} = \min\left\lfloor v_i^{(4)}, x_{i+1}^t - x_i^t - 1 + v_{i+1}^{(4)} \right\rfloor$$

Rule 6. "Moving forward"

$$x_i^{t+1} = x_i^t + v_i^{(5)}$$

where x_i^t is the position of vehicle i at time t, v_i is the velocity of vehicle i, $v_i^{(0)}$ is the velocity $v_i^{(5)}$ at the previous time step $t-1$, defined by x_i^t - x_i^{t-1}, s_i is the number of precedent vehicles from the ith driver's perspective, g_i is the gap between vehicle i and vehicle i+1 (thus, $g_i = x_{i+1}^t - x_i^t - 1$), and V_{max} is the maximum velocity. The notation rand() represents a random number drawn from the uniform distribution on [0, 1]. The quantities G, q, r, S, P_1, P_2, P_3, and P_4 are model parameters. The probability of random braking is given by 1–p_i. We presume $P_1 > P_2 > P_3 > P_4$. As the standard parameter setting, we presumed; model parameters: $q = 0.99$, $r = 0.99$, $S = 2$, $P_1 = 0.999$, $P_2 = 0.99$, $P_3 = 0.98$, $P_4 = 0.01$, $G = 15$, $k = 3$.

2.2 Conventional lane-change model

Although there have been precursors (e.g., [10]), as the conventional sub-model for lane changing, we presume Kukida's rule [1] that considers both gap and velocity difference of surrounding vehicles as below;

Incentive criterion;

$$gap_p^f \leq v_i^{(p)} - v_{i+1}^{(p)} \wedge gap_n^f > v_i^{(p)} - v_{i+1}^{(p)} \wedge gap_n^f > 0$$

Safe criterion;

$$gap_n^b > v_{i-1}^{(n)} - v_i^{(p)} \quad .$$

A vehicle obeying to this protocol (hereafter, called Default) tries lane changing as much as possible whenever meeting with the criteria abovementioned.

2.3 A new lane-change model backed by ITS

Reminding the fact that a range of an intermediate traffic density is volatile since the so-called 'platoon driving', a turbulence brought by lane change irreversibly makes meta-stable phase shift to congestive phase. Thus, it would be expected that a high flux state with such an intermediate density is remained if a meaningless lane change is prohibited. It would be realized in view of ITS by means of additional condition forcefully imposed to a vehicle in order to limit such meaningless lane changes. Let alone, ITS can acquire local information such as traffic density a certain length ahead to a focal vehicle, and can provide it to the focal vehicle.

Concerning the incentive criterion, the presented model considers traffic density ahead to the current position of a focal vehicle, while the safe condition is same as what Default model presuming.

Incentive criterion;

$$gap_p^f \leq v_i^{(p)} - v_{i+1}^{(p)} \wedge gap_n^f > v_i^{(p)} - v_{i+1}^{(p)} \wedge gap_n^f > 0$$
$$\wedge\, \rho_{f \cdot x} > \rho_{cr1} \ \wedge \rho_{f \cdot x} < \rho_{cr2} \ ,$$

where $\rho_{f \cdot x}$ is traffic density next x [m] ahead to a focal vehicle, ρ_{cr1} and ρ_{cr2} are critical density values. With a systematic simulations, we identified those parameters to optimize as below; x = 50 [m], ρ_{cr1} = 0.26 and $\rho_{cr2} = 0.16$.

2.4 Simulation setting

We presume 3-lane system with cyclic boundary of which domain length is 333 cells. Each cell is set to 7.5 [m]. We do with 100 independent realizations starting from different initial configurations for each traffic density in order to obtain a robust statistical result. After a flow field being fully developed, we measure following properties; traffic flux observed at a certain location, time averaged velocity of each vehicle during making a circuit, times of lane changes each vehicle does during making a circuit.

3. Result and discussion

Figure 1 shows traffic flux drawn on 2-dimensional plane of traffic density and lane change frequency. Again, we defined lane change frequency as expected times of lane changes a single vehicle takes during making a circuit. There are three flux lines; green line presuming no lane change allowed, blue line presuming Default (described in Section 2.2) and red line in which our new proposing model (described in Section 2.3) is presumed. We rend you that green line and blue line respectively indicate traffic fluxes with minimal (zero) and maximal (as much as possible) lane change frequencies. Thus, the curving surface linearly connecting green and blue lines physically means the slope of traffic flux with increase of unit lane change frequency. That is to say we could insist that our new protocol for lane changing only allows meaningful lane changes but hampers meaningless ones in terms of global traffic flux, if the red line is beyond this curving surface. And Fig. 1 proves this statement is true. Herein, what we terming 'meaningful (meaningless) lane change' implies a lane-change giving less (much) amount of turbulence into the flow filed that enables flux over (below) the curving surface (interpolated flux between non lane changing case and maximal lane changing case) at its density.

In the following text, let us be concerned on social dilemma analysis. Suppose a multi-player and two-strategy game, where all vehicles in the domain are players. Let a vehicle never taking lane change be Cooperator (hereafter, denoted by C) and one taking lane changes be Defector (hereafter, denoted by D). As for defective strategy D takes, we presume two cases; one is obeying to Default where a vehicle lane-changes as much as possible to increase individual payoff, another is taking the present new lane change protocol. Payoff for strategy; either C or D is evaluated by average velocity (inversely meaning travel time) of all vehicles taking C or D, while social average payoff is evaluated by traffic flux.

According to rich stock about the evolutionary game theory (e.g., [11] – [12]), we would be able to classify the game class; either D-dominate (like Prisoner's Dilemma), Polymorphic (like Chicken (Snowdrift) game), Bi-stable (Like Stag Hunt) or C-dominate (Trivial game; no dilemma game) by exploring three functions; Cooperator's payoff (Π_C), Defector's payoff (Π_D),and social average payoff (Π_{social}) varying with cooperators fraction in the domain. Again, Π_C and Π_D are evaluated average velocity while Π_{social} is quantified by traffic flux.

Figure 2 shows Π_C , Π_D and Π_{social} vs cooperation fraction in case of traffic density of 0.2 with presuming not only Default model but also Proposed model for C, as one example. At any cooperation fraction, Defectors payoff outperforms that of Cooperator, which leads Nash equilibrium to be appeared at the situation of none of cooperators (all-defectors-state). Also we can confirm that the cooperation fraction showing maximal Π_{social} is inconsistent with Nash equilibrium. Because of those two facts, D-dominate, or say, Prisoner's Dilemma structure as social dilemma lies behind this traffic field presuming both Default model and Proposed model for lane change rule and traffic density of 0.2.

If there is social dilemma, we can quantify dilemma strength; η ([3] - [6], [11], [13]) defined as below;

$$\eta = \frac{\Pi_{social}^{max} - \Pi_{NE}}{\Pi_{social}^{max}} = \frac{q_{social}^{max} - q_{NE}}{q_{social}^{max}},$$

where Π_{social}^{max} (q_{social}^{max}) and Π_{NE} (q_{NE}) are maximal social average payoff (traffic flux) and social average payoff (traffic flux) at Nash equilibrium. Obviously, social average payoff (traffic flux) in Proposed model is more stable than Default model, then dilemma strength in Proposed model is lower than Default model.

Figure 3 compares the dilemma strength varying traffic density between presuming Default and our new protocol for defector's lane changing rule. It is quite worthwhile to note that our new lane change protocol is able to mitigate social dilemma significantly as compared with Default model. It is because our new protocol premising the introduction of ITS restricts meaningless lane changes especially in intermediate density range, which remains traffic flux as comparable level as the case with none of lane changing at all. Consequently, it significantly relaxes social dilemma laying behind the traffic field.

4. Conclusion

Premising powerful ITS in our future, we establish a new protocol to control lane changing behavior amid drivers. The key concept is restricting 'meaningless' lane changes taking place in intermediate density range in relation with Meta-stable phase but allowing 'meaningful' lane changes to improve traffic efficiency.

We confirmed the present protocol working better than the conventional rule based on classic incentive criterion.

We also analyze social dilemma structure lying behind traffic field. The present protocol significantly relaxes dilemma strength vis-à-vis the conventional rule.

Acknowledgments

This study was partially supported by SCAT (Support Center for Advanced Telecommunications Technology) Research, Foundation, Kurata Grant and Kakihara Foundation awarded to Professor Tanimoto. We would like to express our gratitude to them.

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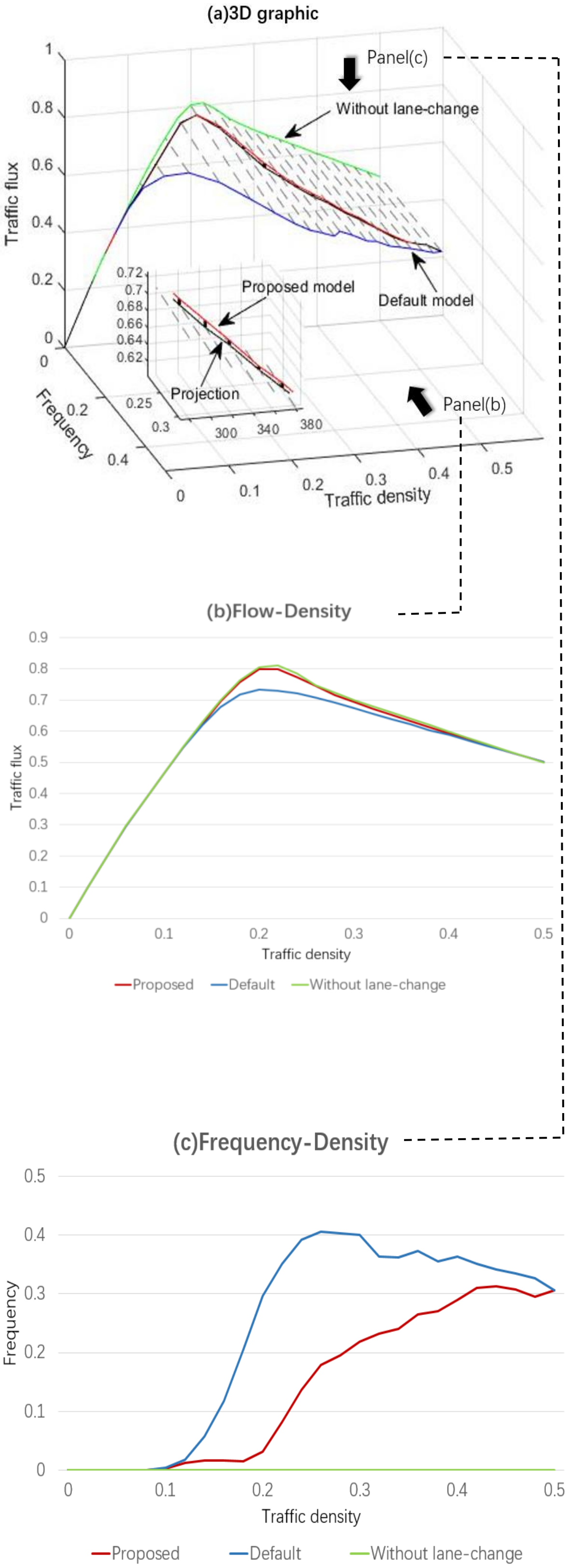

Figure 1. Panel (a) 3D graphic of flux, frequency and global density with enlarging inset. Panel (b) and (c) respectively give flow - density and frequency – density diagrams.

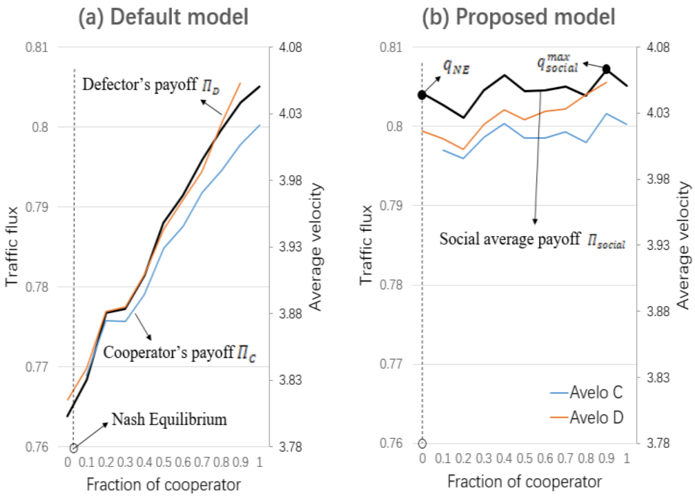

Figure 2. Payoff schematic diagram; (a) Default and (b) Proposed model at traffic density of 0.2.

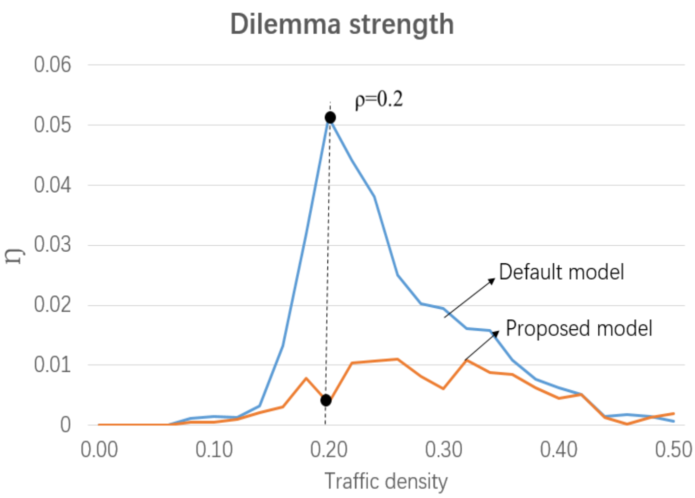

Figure 3. Dilemma strength vs. traffic density. The closed circles indicates the state concerned in Figure 2.